

## Neutron star versus heavy-ion data: is the nuclear equation of state hard or soft?

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Recent astrophysical observations of neutron stars and heavy-ion data are confronted with our present understanding of the equation of state of dense hadronic matter. Emphasis is put on the possible role of the presence of hyperons in the interior of compact stars. We argue that data from low-mass pulsars provide an important cross-check between high-density astrophysics and heavy-ion physics.

*Keywords:* nuclear equation of state; neutron stars; pulsars; kaon production in heavy-ion collisions

### 1. Introduction

The research areas of high-density astrophysics, as the physics of compact stars, and relativistic heavy-ion collisions are probing matter at extreme densities. The properties of neutron stars are determined by the nuclear equation of state (EoS), as well as microphysical reactions in dense matter. The stiffness of the high-density matter controls the maximum mass of compact stars. New measurements of the global properties of pulsars, rotation-powered neutron stars, point towards large masses and correspondingly to a rather stiff equation of state (for a recent review on the equation of state for compact stars see<sup>1</sup>). In a recent analysis of the x-ray burster EXO 0748–67 it was even claimed that soft nuclear equations of state are ruled out.<sup>2</sup> Note that this analysis, if confirmed, would not rule out the presence of quark matter in the core of compact stars.<sup>3</sup>

On the other side, strange particles (kaons) produced in relativistic heavy-ion collisions just below the threshold of the elementary reaction are sensitive to medium effects due to the created high-density matter (see e.g.<sup>4</sup>). Recent investigations conclude that the systematics of kaon production can only be explained by an extremely soft nuclear equation of state above normal nuclear matter density.<sup>5–8</sup>

There seems to be conflict in determining the nuclear equation of state, which we

will discuss in detail in the following. We investigate the impacts of the compression modulus and symmetry energy of nuclear matter on the maximum mass of neutron stars in view of the recent constraints from heavy-ion data on kaon production in dense matter. In particular, we delineate the different density regions probed in the mass-radius diagram of compact stars. We outline the importance of the Schrödinger equivalent potentials for subthreshold production of kaons. The possible effects from the presence of hyperons in dense neutron star matter are confronted with pulsar mass measurements.

## 2. The nuclear EoS from astrophysical and heavy-ion data: a soft or hard EoS?

The properties of high-density nuclear matter is intimately related to the phase diagram of quantum chromodynamics (QCD), for a review see e.g.<sup>9</sup> The regime of high temperatures and nearly vanishing baryochemical potential is probed by present and ongoing heavy-ion experiments at BNL's Relativistic Heavy-Ion Collider and CERN's Large Hadron Collider and is related to the physics of the early universe. A rapid crossover transition due to chiral symmetry restoration and deconfinement is found in lattice gauge simulations, see e.g.<sup>10</sup> The QCD phase diagram at large baryochemical potential and moderate temperatures constitutes the region of the chiral phase transition and the high-density astrophysics of core-collapse supernovae and compact stars (see e.g.<sup>11</sup> for a recent treatise). Terrestrial heavy-ion experiments, as the Compressed Baryonic Matter (CBM) experiment at GSI's Facility for Antiproton and Ion Research (FAIR) will investigate this fascinating and largely unknown terrain of the QCD phase diagram.<sup>12</sup>

The nuclear equation of state serves as a crucial input for simulations of core-collapse supernovae,<sup>13</sup> neutron star mergers,<sup>14,15</sup> proto-neutron star evolution<sup>16</sup> and, of course for determining the properties of cold neutron stars.<sup>17</sup> Pulsar mass measurements provide constraints on the stiffness of the nuclear equation of state. Unfortunately, out of the more than 1600 known pulsars, only a few precise mass measurements from binary pulsars are currently available (see<sup>18</sup> and references therein). Still, the undoubtedly upper mass limit is given by the Hulse-Taylor pulsar of  $M = (1.4414 \pm 0.0002)M_{\odot}$ ,<sup>19</sup> the lightest pulsar known is J1756-2251 with a mass of  $M = (1.18 \pm 0.02)M_{\odot}$ .<sup>20</sup> New data on pulsar masses has been presented at the Montreal conference on pulsars (see ns2007.org). The mass of the pulsar J0751+1807, originally with a median above two solar masses with  $M = 2.1 \pm 0.2M_{\odot}$  ( $1\sigma$ ),<sup>21</sup> is now corrected and below the Hulse-Taylor mass limit.<sup>22</sup> However, the mass of the pulsar J0621+1002 was determined to be between 1.53 to 1.80 solar masses ( $2\sigma$ ).<sup>23</sup> Combined data from the pulsars Terzan 5I and J<sup>24</sup> with the pulsar B1516+02B<sup>25</sup> results in a mass limit of 1.77 solar masses for at least one of these pulsars. Measurement of the pulsar J1748-2021B arrives at a lower mass limit of  $M > 2M_{\odot}$ <sup>25</sup> but that could be the mass of a two neutron star system. The analysis of x-ray burster is much more model dependent. For EXO 0748-676 a mass-radius

constraint of  $M \geq 2.10 \pm 0.28 M_\odot$  and  $R \geq 13.8 \pm 1.8$  km has been derived,<sup>2</sup> for a critical discussion on the analysis I refer to.<sup>26</sup> That constraint would actually rule out soft nuclear equations of state but not the presence of quark matter, as quark matter is an entirely new phase which can be rather stiff.<sup>3</sup>

High-density nuclear matter is produced in the laboratory for a fleeting moment of time in the collisions of heavy nuclei at relativistic bombarding energies. The properties of kaons can change substantially in the high-density matter created. The in-medium energy of kaons will increase with density (basically due to the low-density theorem, see however<sup>27</sup> which arrives at a somewhat stronger repulsive potential). Kaons are produced by the associated production mechanism  $NN \rightarrow NAK$ ,  $NN \rightarrow NNK\bar{K}$ , and most importantly by the in-medium processes  $\pi N \rightarrow \Lambda K$ ,  $\pi \Lambda \rightarrow N\bar{K}$ , which are rescattering processes of already produced particles. The effective energy of kaons in the medium will change the Q-values of the direct production and rescattering processes, therefore affecting the net production rate.<sup>4</sup> As kaons have long mean free paths, they can leave the high-density region and serve as an excellent tool to probe its properties. Indeed, detailed transport simulations find that nuclear matter is compressed up to  $3n_0$  for a typical bombarding energy of 1 to 1.5 AGeV and that the produced kaons are dominantly produced around  $2n_0$ , where  $n_0$  stands for the normal nuclear matter saturation density.<sup>6,7</sup> Kaons are produced below the elementary threshold energy due to multi-step processes which increase with the maximum density achieved in the collisions. The double ratio of the multiplicity per mass number for the C+C collisions and Au+Au collisions turns out to be rather insensitive to the input parameters (elementary cross sections, in-medium potential) which scale linearly with mass number or density. Only calculations with a compression modulus of  $K \approx 200$  MeV can describe the trend of the kaon production data.<sup>5-8</sup> Hence, the analysis of heavy-ion experiments points towards a rather soft nuclear equation of state.

### 3. The different density regimes of neutron stars

In the following we discuss the different densities encountered in neutron stars and the corresponding regions in the mass-radius diagram. While the standard lore is that the crust of a neutron star consists of nuclei, neutrons and electrons, the composition of the interior of a neutron star is basically unknown. At about  $2n_0$  hyperons can appear as a new hadronic degree of freedom. Kaons can be formed as Bose-Einstein condensate. Finally, chirally restored quark matter can be present as an entirely new phase in the core of compact stars. After considering pure nucleonic matter, we focus on the role of hyperons and their importance for the properties of neutron stars (see also<sup>28</sup> and references therein).

First, let us consider just nucleonic matter. Its equation of state can be modelled by a Skyrme-type ansatz for the energy per nucleon. The parameters are fixed by the nuclear matter properties, as the saturation density, binding energy, compression modulus and asymmetry energy.<sup>29</sup> In addition, we explore effects from the asym-

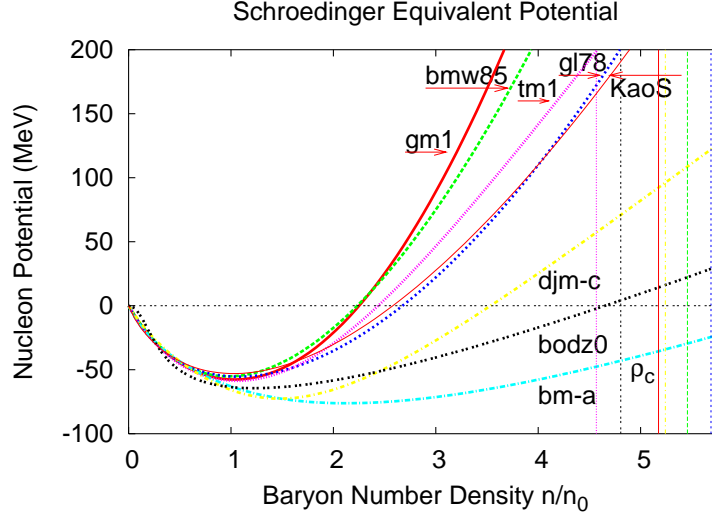


Fig. 1. The Schrödinger equivalent potential versus the baryon number density given in  $n_0$  for various parameters of the relativistic mean-field model.

metry term having a density dependence which scales with a power  $\alpha$  as extracted from heavy-ion collision measurements where  $\alpha$  is between 0.7 and 1.1.<sup>30–32</sup> The pressure is determined by a thermodynamic relation, which fixes completely the EoS used in transport simulations of heavy-ion collisions. With that EoS at hand one can check now, whether the low compressibilities found in describing the kaon production data of  $K \approx 200$  MeV<sup>5–8</sup> are ruled out by neutron star measurements.

Solving the Tolman-Oppenheimer-Volkoff equation gives the result that rather large maximum neutron star masses can be reached even for such low values of the compression modulus.<sup>29</sup> The maximum mass is greater than  $M > 2M_\odot$  for a compression modulus of  $K > 160$  MeV ( $\alpha = 1.0, 1.1$ ) and for the case  $\alpha = 0.7$  greater than  $M > 1.6M_\odot$  for  $K > 160$  MeV and greater than  $M > 2M_\odot$  for  $K > 220$  MeV. Changing the asymmetry energy within reasonable values ( $S_0 = 28$  to 32 MeV) shifts the maximum mass by at most  $\Delta M = \pm 0.1M_\odot$  for low values of  $K$ . The maximum central density is about  $n_c = (7 \div 8)n_0$  for  $\alpha = 1.0, 1.1$  and can hit even  $10n_0$  for  $\alpha = 0.7$ . The EoS is causal up to a compression modulus of  $K = 340$ , corresponding to a maximum mass of  $M = 2.6M_\odot$ , for  $\alpha = 1.0, 1.1$  and up to  $K = 280$  MeV for  $\alpha = 0.7$ . Hence, we conclude that even a pulsar mass of  $2M_\odot$  would be compatible with the 'soft' EoS as extracted from heavy-ion data. This statement is corroborated by more advanced many-body approaches to the nuclear EoS for kaon production in heavy-ion collisions and neutron star mass limits.<sup>33</sup>

For a field-theoretical investigation on the nuclear equation of state in heavy-ion collisions and for neutron stars one has to consider the Schrödinger equivalent potential, which is the actual input to the transport simulation codes, not the nuclear

equation of state. There is a one-to-one correspondence between the energy per baryon and the nucleon potential for the non-relativistic Skyrme model as studied above. However, this direct relation is lost in a relativistic field theoretical approach as for example the relativistic nucleon potential exhibits now a scalar and vector part. We note also, that the direct relation between the compression modulus  $K$  and the stiffness of the nuclear equation of state at supra-nuclear densities is also lost. The stiffness of the EoS in the standard relativistic mean-field (RMF) model is controlled by the effective mass of the nucleon at saturation density not by the compression modulus, which is actually well known for quite some time, see e.g.<sup>34</sup> The Schrödinger equivalent potential for a sample of parameter sets of the relativistic mean-field model is depicted in Fig. 1. The line marked 'KaoS' stands for the nucleon potential as used in transport simulations for a compression modulus of  $K = 200$  MeV. In order to be in accord with the KaoS data, the potential of the relativistic mean-field parameter set should be below the curve labelled 'KaoS' at a density region of around  $2n_0$  where most of the kaons are produced at subthreshold collision energies. The parameter sets used for the standard nonlinear RMF model are 'bmw85' with an effective mass of  $m^*/m = 0.85$  and  $K = 300$  MeV,<sup>34</sup> 'gm1' with  $m^*/m = 0.7$  and  $K = 300$  MeV, and 'gl78' with  $m^*/m = 0.78$  and  $K = 240$  MeV.<sup>35</sup> Note, that the values chosen for the effective nucleon mass are quite high so that the nuclear EoS becomes soft. Typical fits to properties of nuclei arrive at values of  $m^*/m \approx 0.6$  as for the parameter set 'tm1' which is fitted to properties of spherical nuclei.<sup>36</sup> The set 'tm1' has an additional selfinteraction term for the vector fields which results in an overall similar behaviour of the nucleon potential in comparison to the other RMF parameter sets with a soft EoS. Those vector selfinteractions were introduced in<sup>37</sup> where the set 'bodz0' with  $m^*/m = 0.6$  and  $K = 300$  MeV is taken from. One motivation of introducing this vector selfinteraction term is to describe the nucleon vector potential as computed in more advanced many-body approaches which are based on nucleon-nucleon potentials. For the sets 'bm-a' and 'djm-c', the vector selfenergy of the nucleon in the RMF calculation was adjusted to the ones of Dirac-Brueckner-Hartree-Fock calculations.<sup>38</sup> The minima of the nucleon potential of those latter three parameter sets are located at larger densities than the saturation density, in particular for the set 'bm-a'. We stress that the nuclear equation of state for those sets, however, gives the right properties of saturated nuclear matter.<sup>38</sup> Fig. 1 shows also the maximum density reached in the center of the maximum mass configuration of the neutron star sequence by vertical lines, which are surprisingly close lined up between  $4.5$  to  $6n_0$  in view of the large differences in the nucleon potential at high densities.

The mass-radius diagram for the RMF parameter sets giving a small Schrödinger equivalent potential, i.e. one which is at or below the potential used in transport simulations ( $K = 200$  MeV), is plotted in Fig. 2 for neutron star matter consisting of nucleons and leptons only. The sets 'gl78' and 'djm-c' reach maximum masses of  $2.04M_\odot$  and  $1.98M_\odot$ , respectively, even though the nucleon potential for the set 'djm-c' is well below the limit given from the heavy-ion data analysis (see Fig. 1).

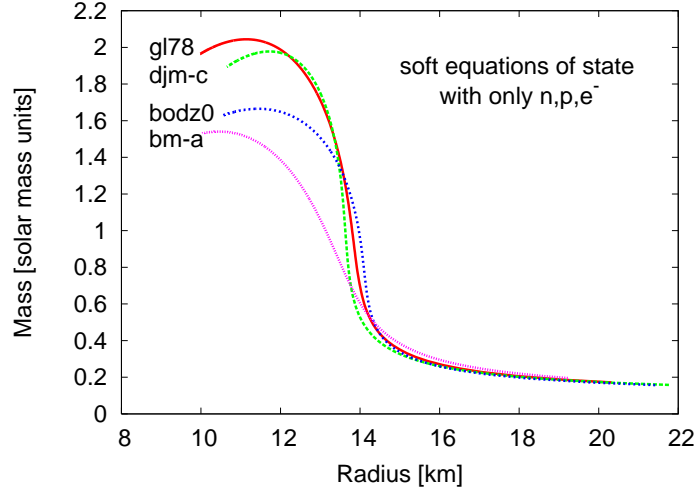


Fig. 2. The mass-radius plot for various parameter sets of the relativistic mean-field model with nucleons and leptons only.

The sets 'bodz0' and 'bm-a' just arrive at maximum masses of  $1.66M_{\odot}$  and  $1.54M_{\odot}$ , respectively, which could be ruled out with a confirmed measurement of a heavy pulsar but so far can not be excluded. It seems, that the constraint from heavy-ion data on the nucleon potential alone is in agreement with pulsar mass measurements for relativistic mean-field approaches, even if masses of about  $2M_{\odot}$  will be measured in the future. An important point to stress here is that the heavy-ion data and the determination of the maximum mass of neutron stars addresses completely different density regimes. While the heavy-ion data on kaon production probes at maximum 2 to  $3n_0$ , the central density of the most massive neutron stars tops  $5n_0$ . Hence, the maximum mass of neutron stars probes the high-density regime of the nuclear equation of state which is not constrained by the heavy-ion data presently available. In other words, if the pressure, or better the nucleon potential, rises slowly at densities up to  $2n_0$ , it could increase rapidly at larger densities so as to comply with astrophysical data on neutron star masses. Moreover, new particles and phases could certainly appear at such large densities which change the equation of state for massive neutron stars substantially, as hyperon matter, to which we turn now for making our argumentation more explicit.

The in-medium properties of hyperons are constrained by hypernuclear data. In particular, the  $\Lambda$  potential at  $n_0$  is quite well determined to be  $-30$  MeV. Other hyperon potential are much less well known, unfortunately. Hyperons, if present, have a strong impact on the properties of compact stars (see<sup>28</sup> for a recent outline).  $\Lambda$  hyperons constitute a new hadronic degree of freedom in neutron star matter at and above about  $2n_0$ . The population of other hyperons,  $\Sigma$  and  $\Xi$  hyperons, is highly sensitive to their in-medium potentials. For a slightly repulsive potential

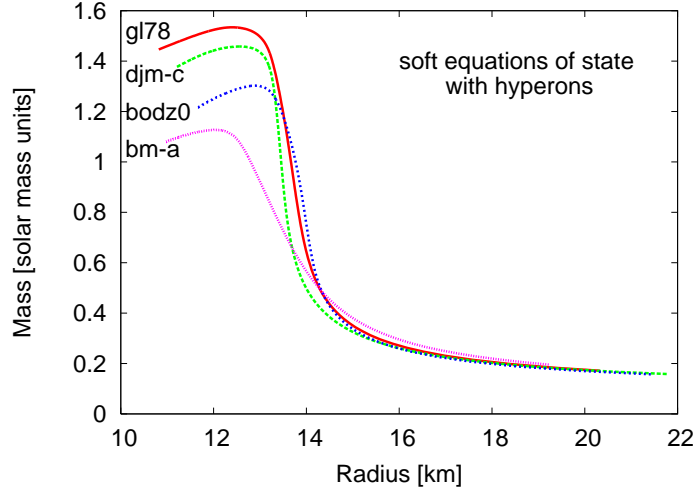


Fig. 3. The mass-radius plot for various parameter sets of the relativistic mean-field model including the effect of hyperons.

for the  $\Sigma$  these hyperons do not appear in compact star matter at all. The  $\Xi$  hyperons will be present, as their in-medium potential is likely to be attractive. The presence of hyperons changes drastically the properties of compact stars. The new degree of freedom lowers the pressure for a given energy density, so that the EoS is considerably softened at large densities. There is a substantial decrease of the maximum mass due to the appearance of hyperons in compact stars: the maximum mass for such “giant hypernuclei” can drop down by  $\Delta M \approx 0.7M_{\odot}$  compared to the case of neutron star matter consisting of nucleons and leptons only.<sup>35</sup> For the RMF parameter sets studied here, we add hyperons as outlined in<sup>39</sup> by fixing the hyperon vector coupling constants via SU(6) symmetry relations and the hyperon scalar coupling constant to the (relativistic) hyperon potentials as determined in<sup>40</sup> from hypernuclear data and hyperonic atoms. The resulting mass-radius plot when including hyperons is pictured in Fig. 3. Note the different mass scales of Figs. 2 and 3, the maximum mass with hyperons included is now substantially decreased to  $1.53M_{\odot}$  for the set ‘gl78’, to  $1.46M_{\odot}$  for the set ‘djm-c’, to  $1.30M_{\odot}$  for the set ‘bodz0’, and to  $1.27M_{\odot}$  for the set ‘bm-a’. The latter two cases are now even below the Hulse-Taylor mass limit and can be ruled out. The former two cases are just above the Hulse-Taylor mass limit of  $1.44M_{\odot}$  and could be ruled out if measurements of heavy neutron star masses of  $1.6M_{\odot}$  or more will be confirmed in future astrophysical observations. Clearly, the presence of hyperons in compact stars could be severely constrained by combining the heavy-ion data analysis with the measurement of a heavy neutron star. The limit on the nucleon potential from heavy-ion data seems to make it quite difficult to reach neutron star masses above say  $1.6M_{\odot}$  for the RMF model when hyperons are included via SU(6) symmetry

and by adopting the presently (sometimes poorly) known hyperon potentials from hypernuclear data. Of course, a much more systematic analysis needs to be done, a firm statement can not be drawn from our sample of parameter sets. Certainly, the situation could be changed for other many-body approaches. Within the relativistic Hartree-Fock approach, for example, maximum masses of about  $1.9M_{\odot}$  are possible even when effects from hyperons are added to the equation of state.<sup>41</sup> But one rather robust conclusion can be drawn from our analysis: the high-density EoS above  $2n_0$ , where hyperons appear and modify the EoS in the models used here, is crucial in determining the maximum mass of a neutron star. Hence, we are probing this density region when looking at the maximum mass configurations of compact stars.

The procedure to follow is now eminent, the true comparison between the present heavy-ion data and astrophysical data on compact stars is not located in the high-mass region but on the low-mass region of the mass-radius diagram of compact stars. The lightest neutron star known at present is the pulsar J1756-2251 with a mass of  $M = (1.18 \pm 0.02)M_{\odot}$ .<sup>20</sup> Much lower values are probably not realized in nature as hot proto-neutron stars have a much larger minimum stable mass than cold neutron stars, for example a minimum mass of  $0.86M_{\odot}$  has been found for an isothermal proto-neutron star.<sup>42</sup> Interestingly, a  $1.2M_{\odot}$  neutron star has a maximum density of  $n = 2n_0$  in our non-relativistic models,<sup>29</sup> so that exotic matter is likely to be not present. We find that the radius of such a low-mass neutron star is in fact highly sensitive to the nuclear equation of state (see also<sup>43</sup>), in particular to the asymmetry energy at high densities which is well known.<sup>31,44–46</sup> There are several promising proposals for radii measurements of neutron stars, see<sup>1</sup> for a recent overview. The fascinating aspect is that heavy-ion experiments can address this density region and probe not only the equation of state but also the density dependence of the asymmetry energy. The ratio of the produced isospin partners  $K^+$  and  $K^0$  at subthreshold energies has been demonstrated to be sensitive to the isovector potential above saturation density.<sup>47</sup> The tantalising conclusion is that a direct comparison with heavy-ion data and compact star data seems to be feasible.

As always there are exceptions to the assumption, that the nuclear EoS just contains nucleons and leptons up to  $1.2M_{\odot}$ . In Ref.<sup>48</sup> strange quark matter is already present for only  $0.3M_{\odot}$  which depends hugely on the choice of the MIT bag constant. In Ref.<sup>49</sup> hyperons appear already for a compact star mass of only  $0.5M_{\odot}$  although the critical density for the onset of the hyperon population is around  $2n_0$ . The reason is that the equation of state is unphysically soft, so that the maximum mass is below the Hulse-Taylor mass limit. In any case, this provides another opportunity for the radius measurement of low-mass pulsars: if their radii turn out to be completely off the range predicted from our knowledge of the density dependence of the asymmetry energy, some exotic matter is present in the core of neutron stars!



#### 4. Summary

The combined analysis of heavy-ion data on kaon production at subthreshold energies and neutron star mass measurements points towards a nuclear EoS that is soft at moderate densities and hard at high densities. A soft nuclear EoS as extracted from kaon production data is not in contradiction with heavy pulsars as mutually exclusive density regions are probed. The nuclear EoS above  $n \approx 2n_0$  determines the maximum mass of neutron stars, which is controlled by unknown high-density physics (as hyperons and quark matter). Compact star matter constrained by the heavy-ion data seems to result in rather low maximum masses for compact stars when hyperons are included. A measurement of a heavy pulsar will make it quite difficult for having hyperons inside a neutron star and could exhibit an emerging conflict between hypernuclear and pulsar data. Properties of low-mass neutron stars ( $M \leq 1.2M_\odot$ ), however, are likely to be entirely determined by the EoS of nucleons and leptons only up to  $n \approx 2n_0$ , as hyperon and possibly quark matter could appear at larger densities. Thus, the measurement of the radii of low-mass pulsars provides the opportunity for a cross-check between heavy-ion and astrophysical data and possibly for the detection of an exotic phase in the interior of compact stars.

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